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AAS 26-967

Sun-Earth L_2 Point Nulling Interferometry Formation Flying Performance Analysis

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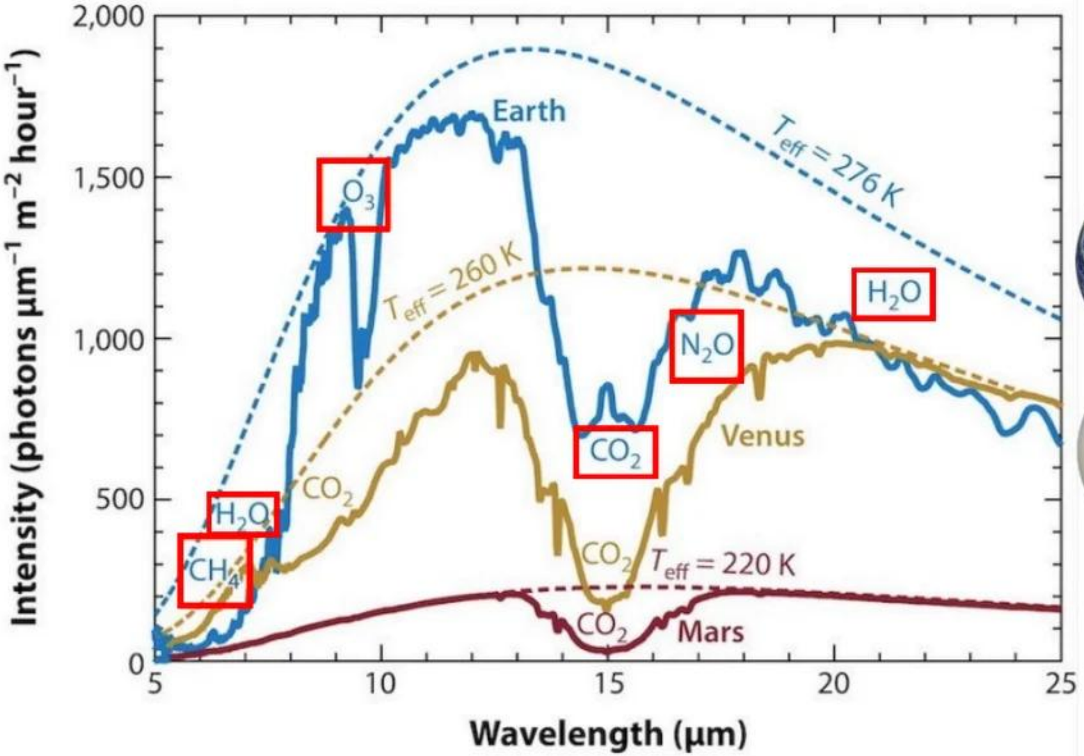
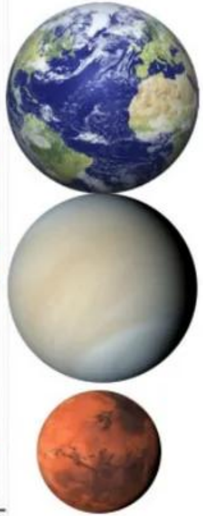
he Goal: Characterize Terrestrial Worlds with LIFE





Wavelength covers peak emission of Earth-like exoplanets

Features absorption bands of O_3, CH_4, N_2O

Thermal emission carries atmospheric information

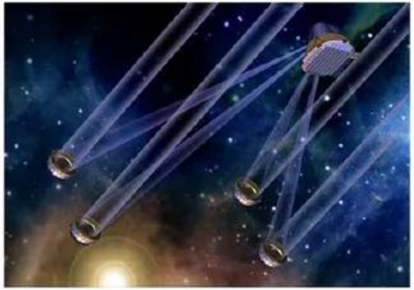
(Credit: Meadows and Crisp, 1996; Tinetti et al., 2005; Tinetti et al., 2006; Kaltenegger et al., 2007; Selsis et al., 2007b)

For a nulling interferometer (e.g., LIFE) there are several mission level design variables that affect the design of both the formation control and the optics.

We study the relative formation error and fuel usage of these key variables.

Formation control and optical control must be co-designed: formation errors couple directly into nulling and modulation errors.

Past Concepts:



TPFI (credit: NASA)

DARWIN (credit: ESA)

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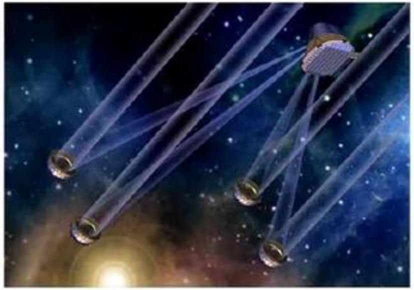

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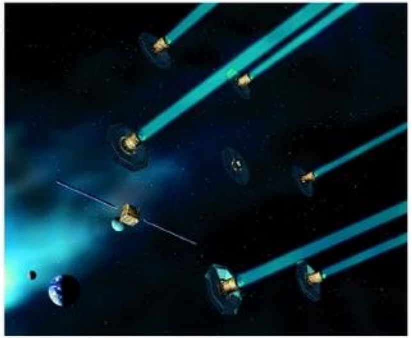
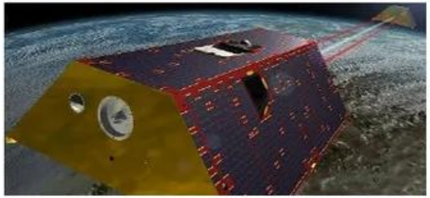


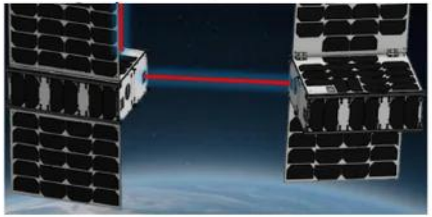
DARWIN (credit: ESA)

Past/Future Tech Demos:

Proba-3 (credit:



GRACE-FO (credit:



STARI (credit: Stanford SRL)

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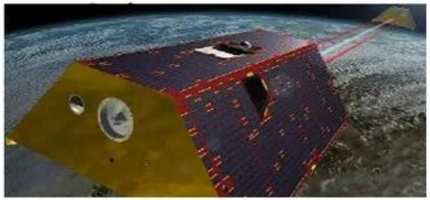

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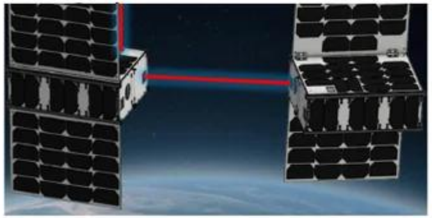
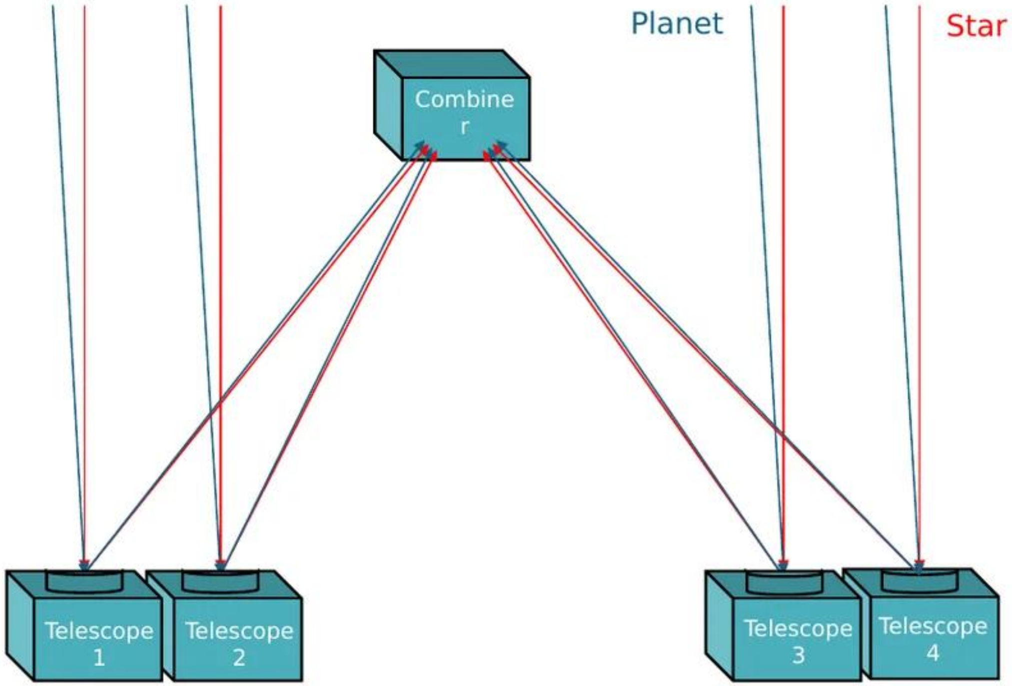


STARI (credit: Stanford SRL)

Inspiration in this Study:

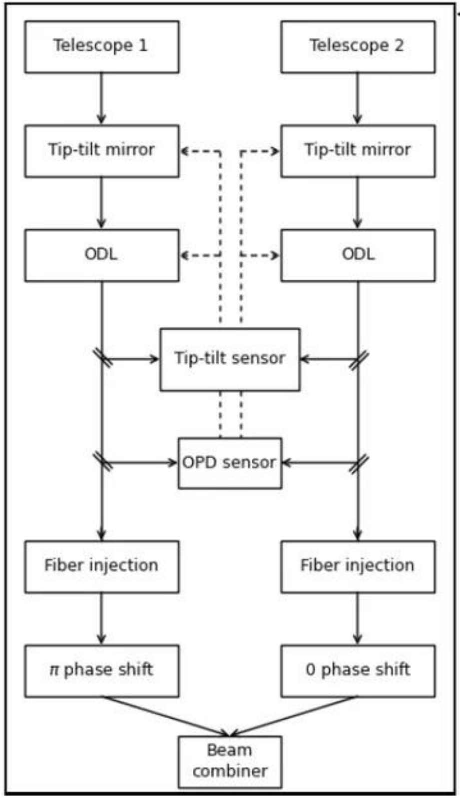
- In-plane vs Out-of-plane (TPFI vs Darwin)
- 12,18, 24 hour rotation rates (TPFI vs LIFE vs Darwin)
- 45, 65, 85 degree pointing angle (TPFI/LIFE/Darwin inspired)
- Sensors inspired by Proba-3, GRACE-FO, and STARI

Nulling Interferometry

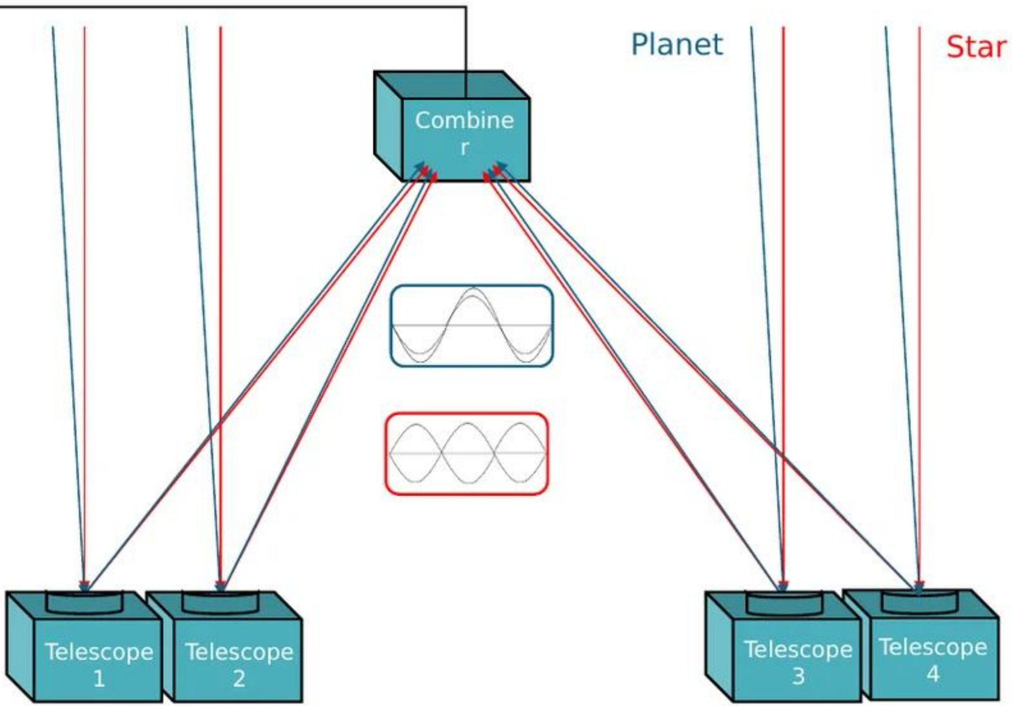


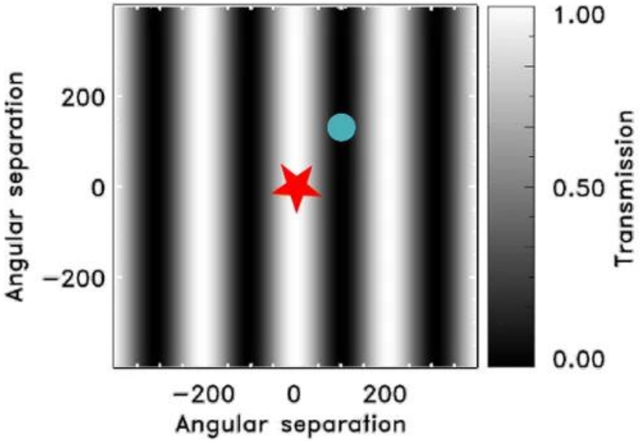
ASTROLAB

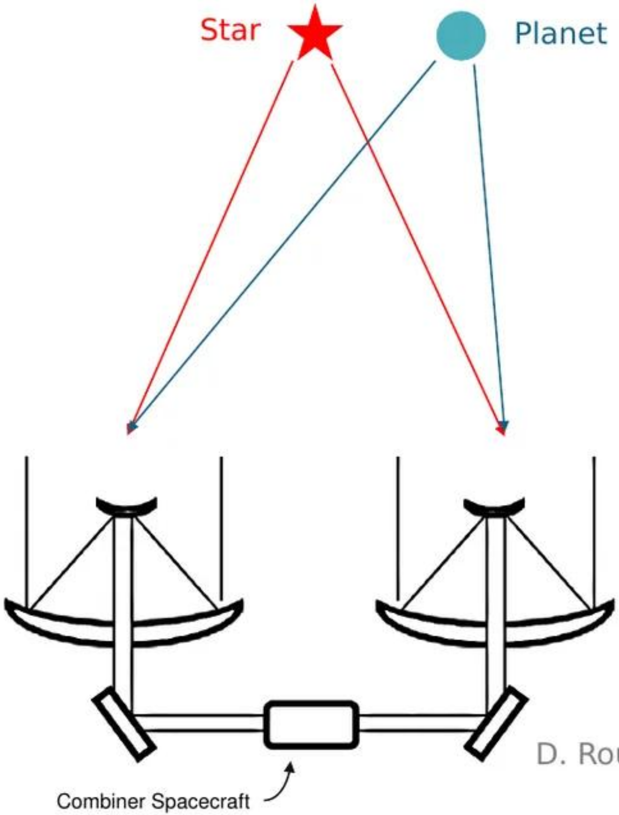
Nulling Interferometry



x2

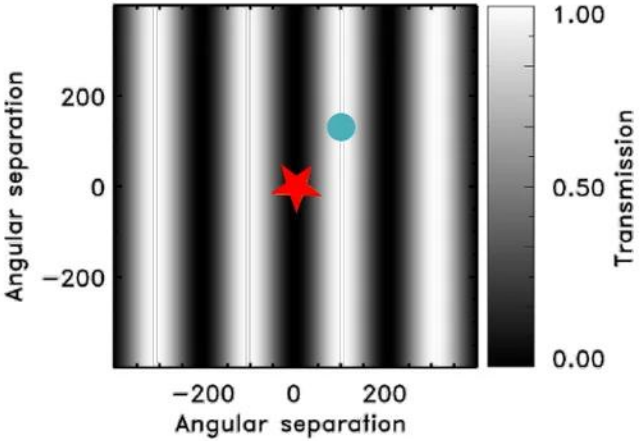






Imaging Interferometer

D. Rouan



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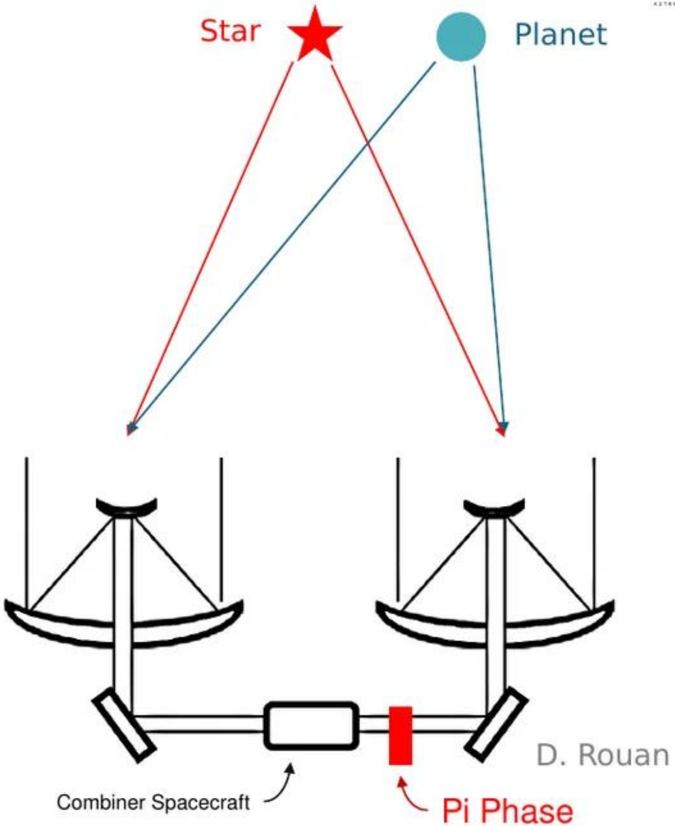
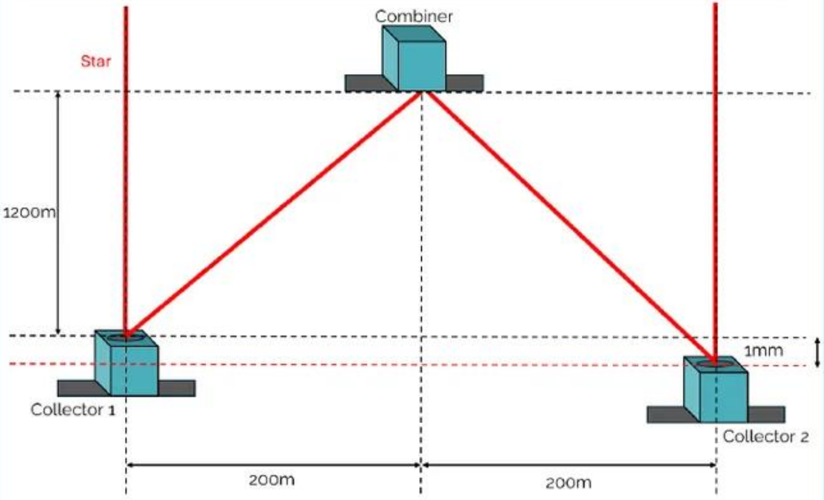


Optical Path Difference / Phase Mismatch

$$\Delta\mathrm{OPD}_{\star,ij} = -\left(\hat{\mathbf{s}}_\star + \hat{\boldsymbol{\rho}}_j\right)^\top \delta\mathbf{r}_j + \left(\hat{\mathbf{s}}_\star + \hat{\boldsymbol{\rho}}_i\right)^\top \delta\mathbf{r}_i$$

$$\hat{\boldsymbol{\rho}}_i = \frac{\mathbf{r}_C - \mathbf{r}_i}{\|\mathbf{r}_C - \mathbf{r}_i\|}$$

$$\boxed{|\delta\mathrm{OPD}_\star| = (1\ \mathrm{mm})\left(1 + \frac{1200}{\sqrt{1200^2 + 200^2}}\right) = 1.986\ \mathrm{mm}}$$



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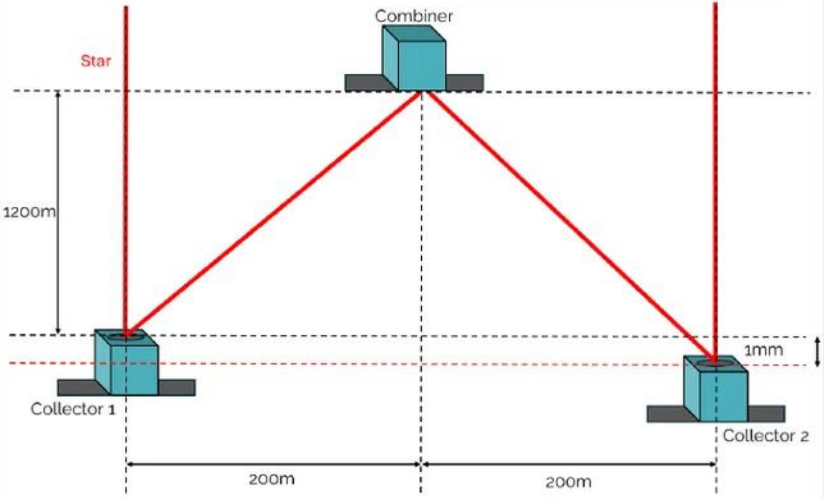
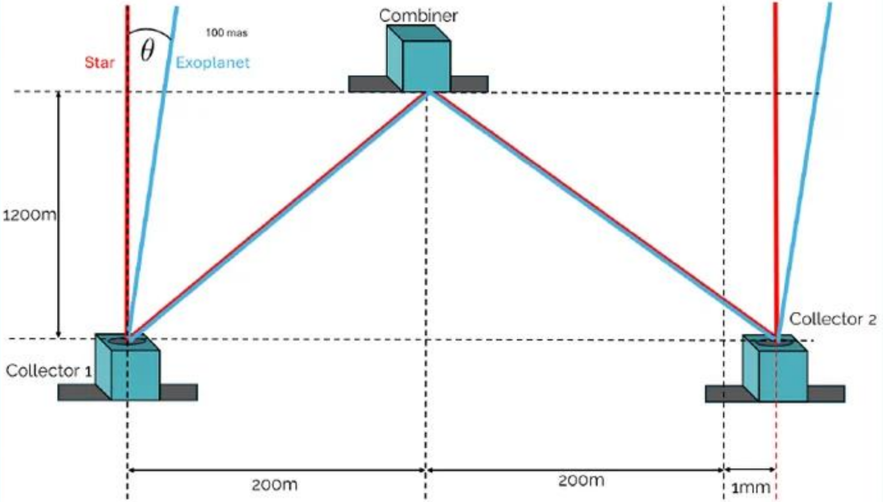


Planet Modulation Error

$$\delta\ell_{p-\star} = \delta\mathbf{b}_{ij}^\top\left(\hat{\mathbf{s}}_p - \hat{\mathbf{s}}_\star\right) \simeq \delta b_\perp \theta$$

$$\boxed{|\delta D_{p-\star}| \simeq \delta b_\perp \theta = \left(10^{-3}\ \mathrm{m}\right)\left(4.848 \times 10^{-7}\right) = 0.485\ \mathrm{nm}}$$



144 Case Trade Study Variables

2 x Controller	PD vs CR3BP-LQI

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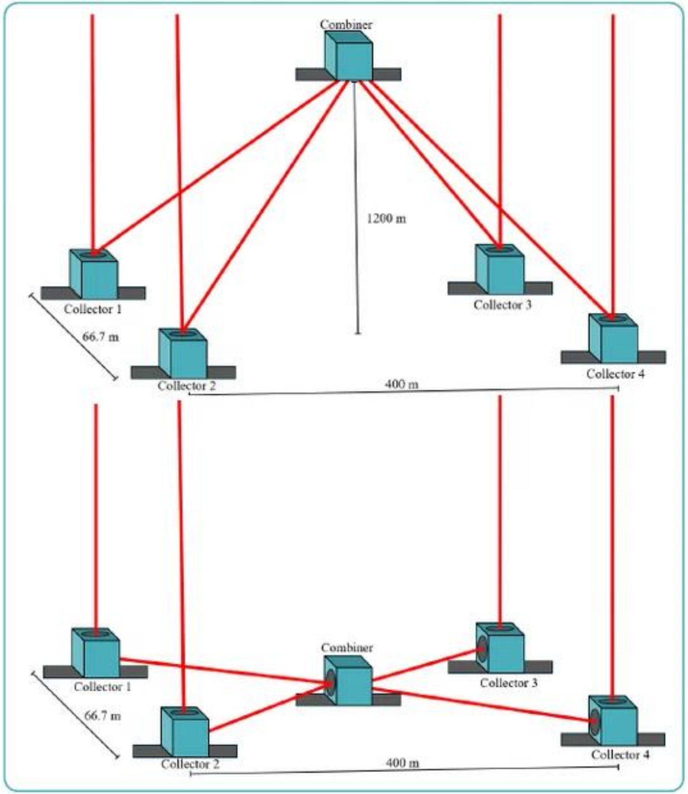
2 x Combiner placement	In-plane combiner vs out-of-plane combiner



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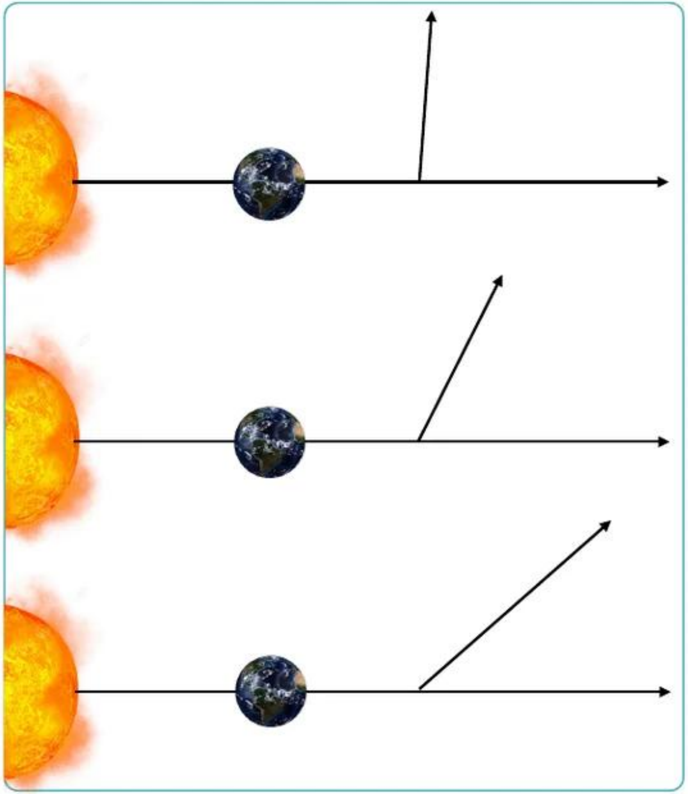

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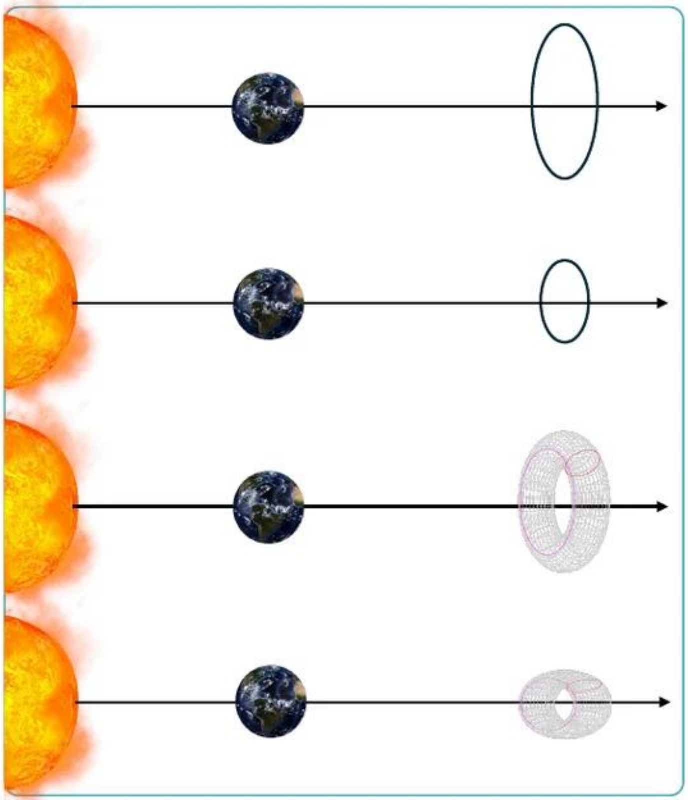
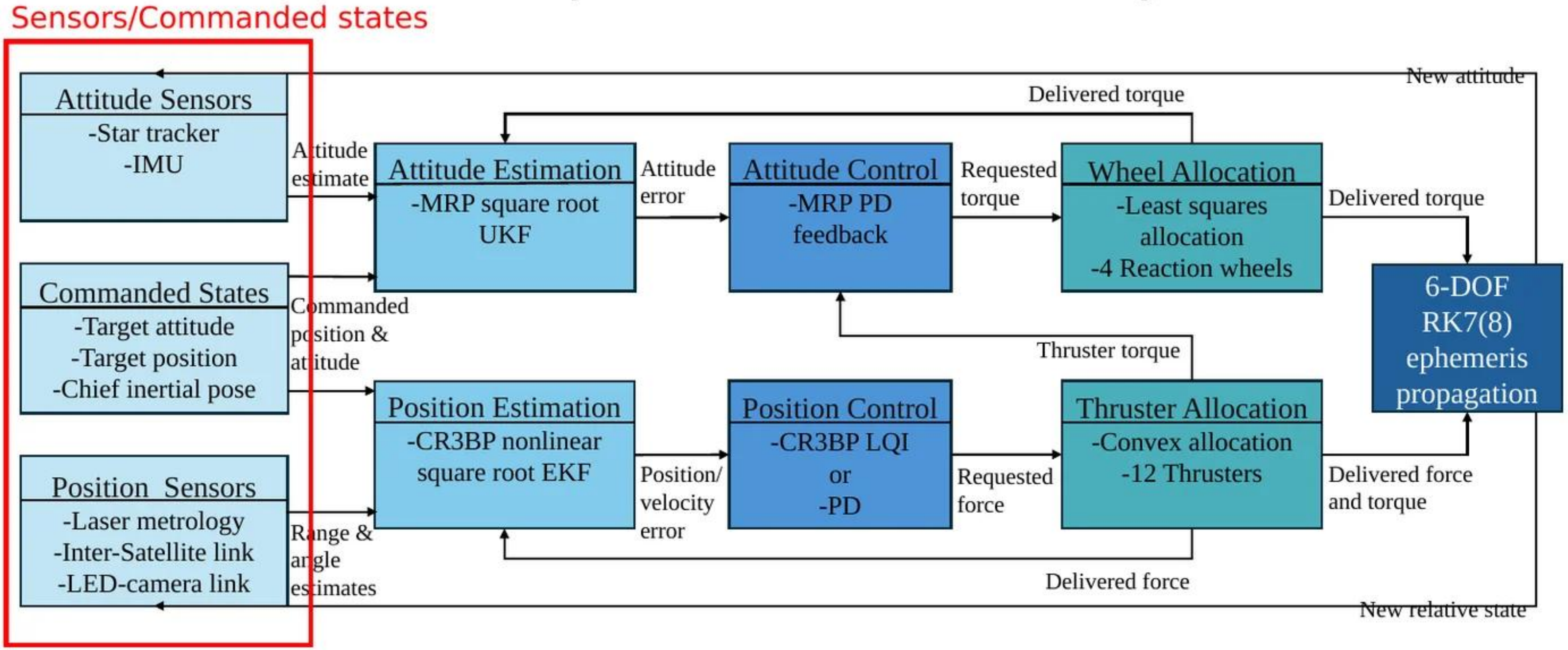
3 x Array rotation	12 h, 18 h, 24 h array-rotation periods
3 x Pointing angle	45°, 65°, 85° line-of-sight cases
4 x Combiner orbit	JWST-like halo; small periodic halo; quasi-halo; Lissajous-family trajectory



Follower Spacecraft Control System



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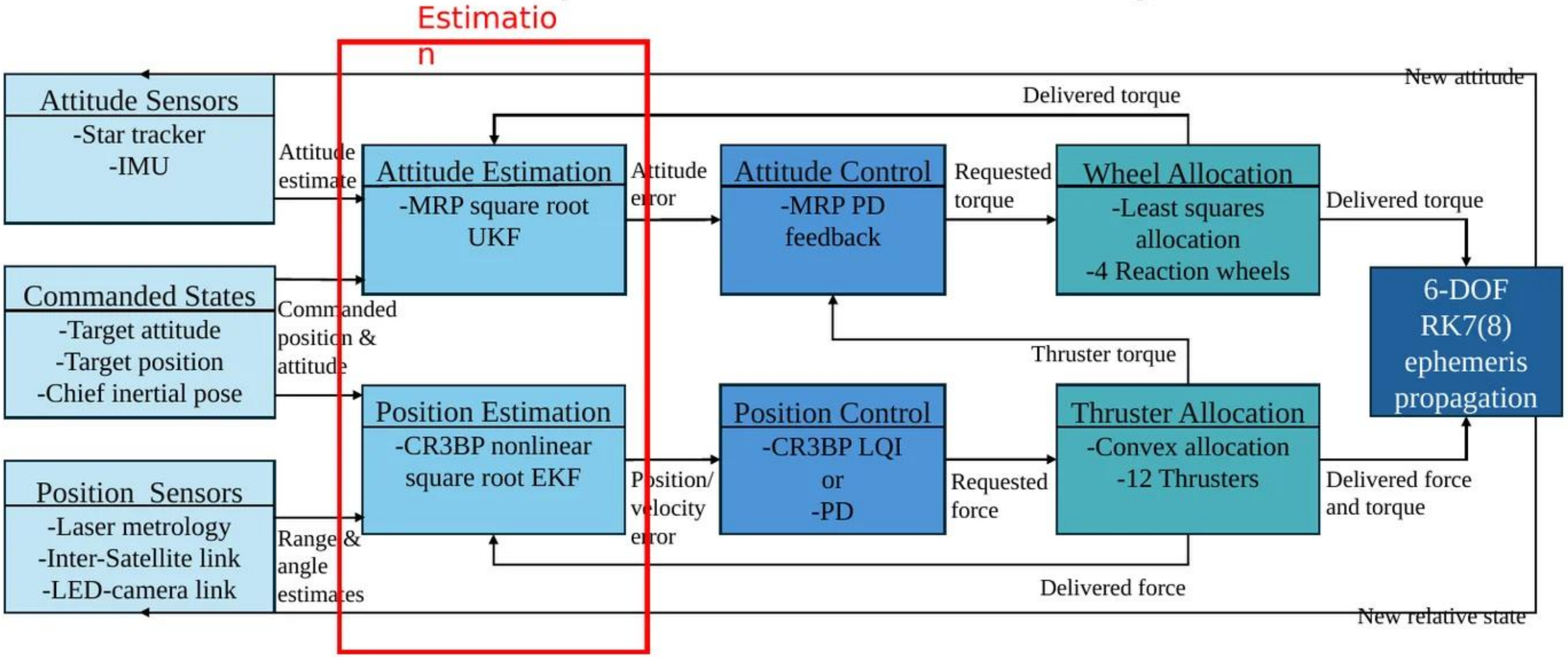

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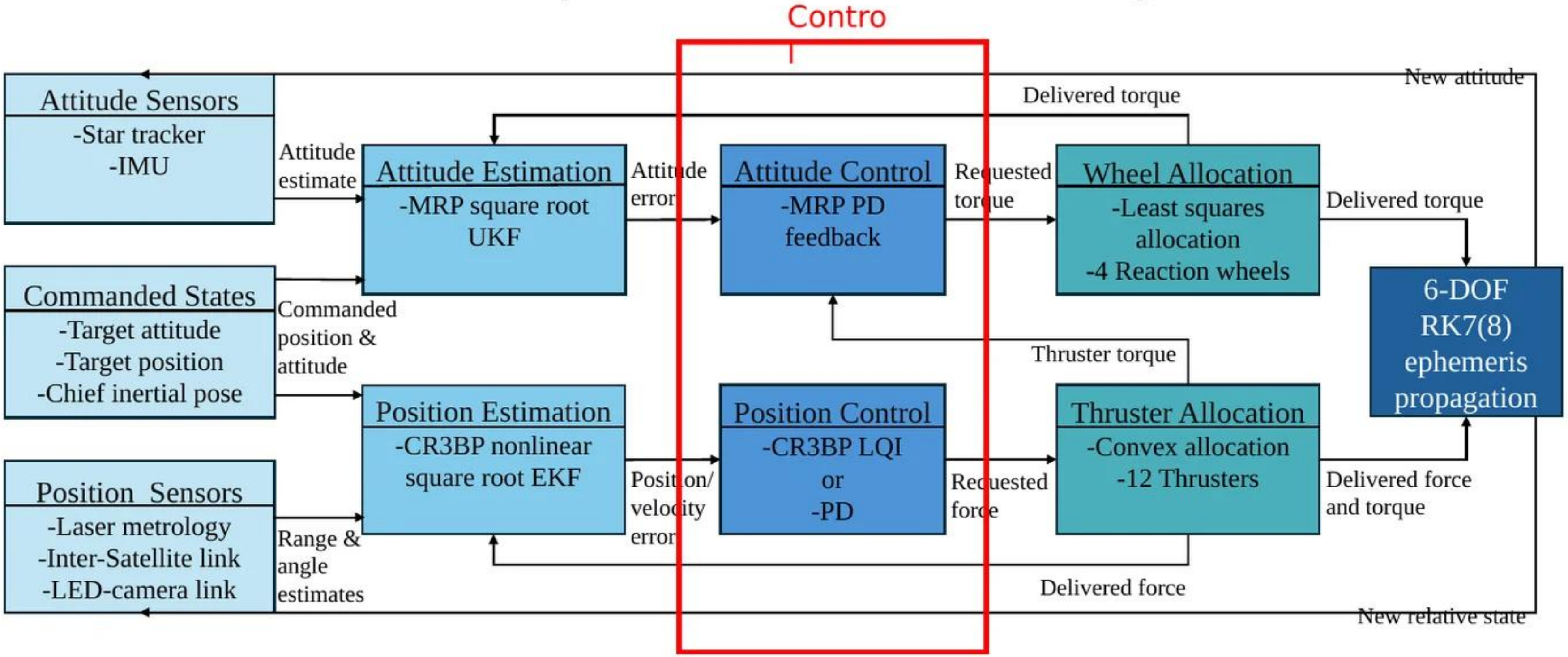

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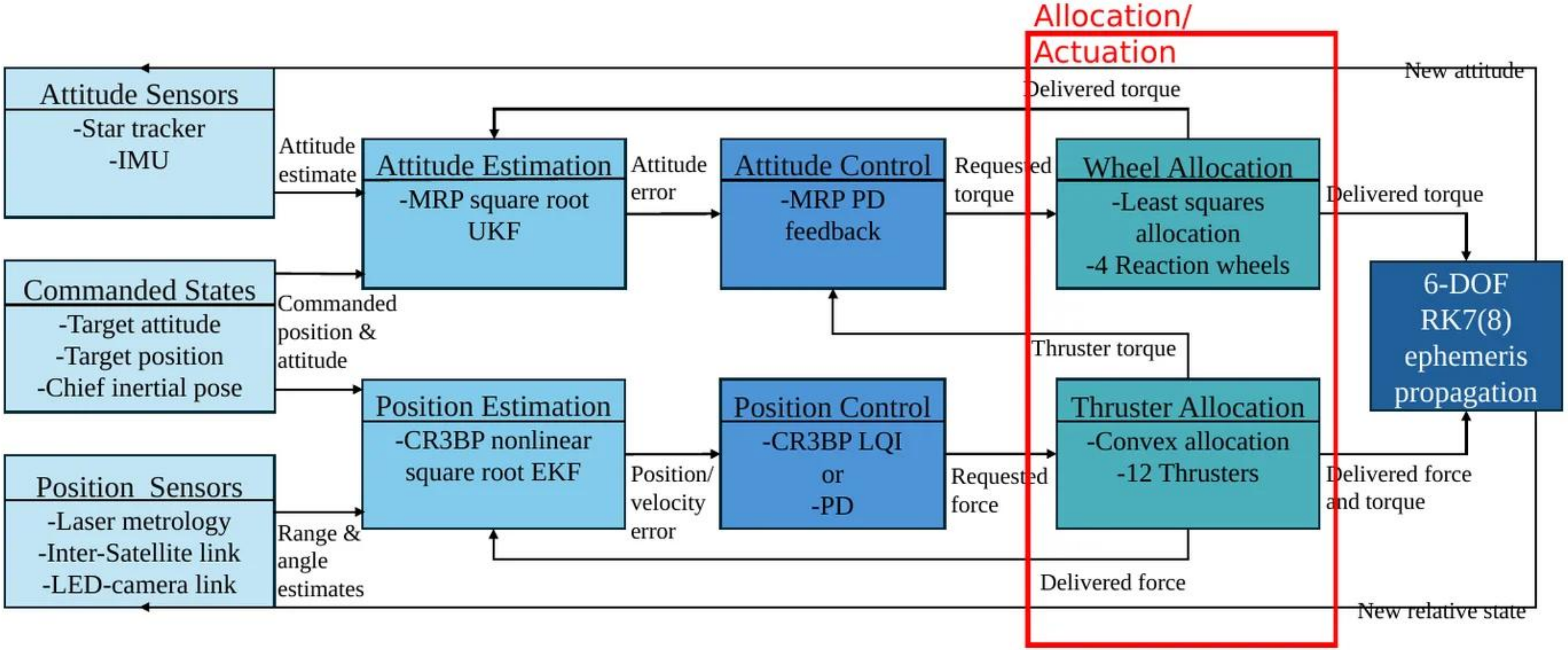

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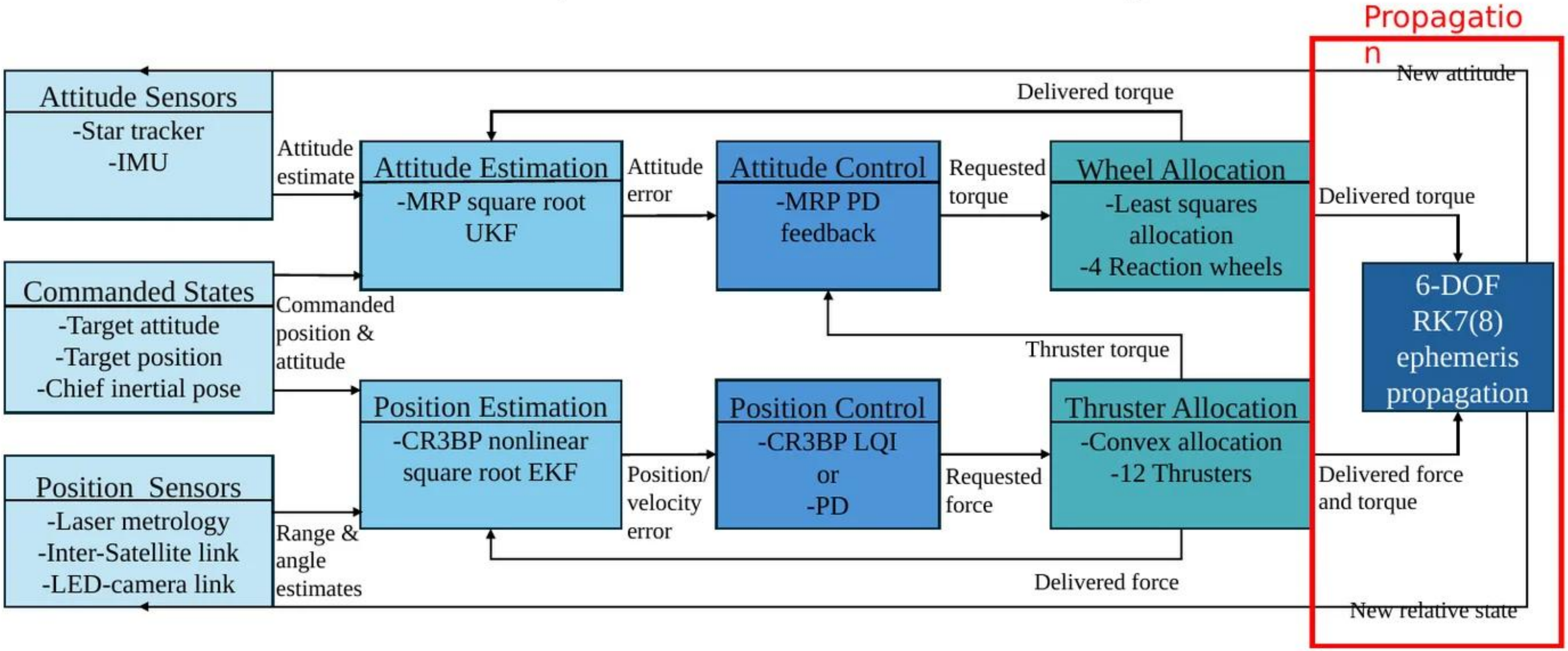
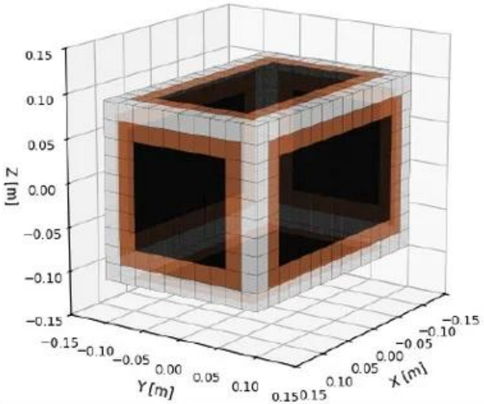


$$m\ddot{\mathbf{r}}_N = \mathbf{F}_{\text{grav}} + \mathbf{F}_{\text{SRP}} + \mathbf{F}_{\text{th}} + \mathbf{F}_{\text{alb/IR}}$$

$$\mathbf{I}_B\dot{\boldsymbol{\omega}}_{BN,B} + \boldsymbol{\omega}_{BN,B} \times (\mathbf{I}_B\boldsymbol{\omega}_{BN,B}) = \boldsymbol{\tau}_{\text{gg}} + \boldsymbol{\tau}_{\text{SRP}} + \boldsymbol{\tau}_{\text{th}} + \boldsymbol{\tau}_{\text{alb/IR}}$$



Each surface area is assigned, normal direction, reflectivity, absorptivity, emissivity, and thermal reradiation.
Forces and torques are summed per surface.

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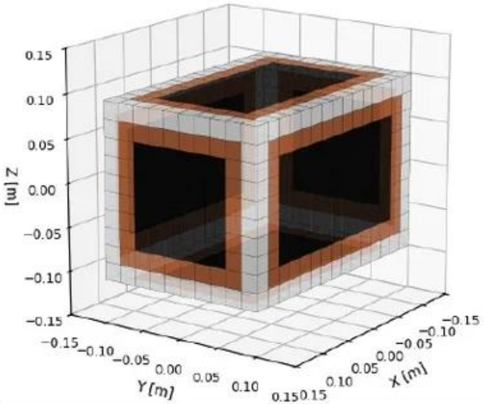

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Gravitational force and torque

$$\mathbf{F}_{\text{grav}} \qquad \boldsymbol{\tau}_{\text{gg}}$$

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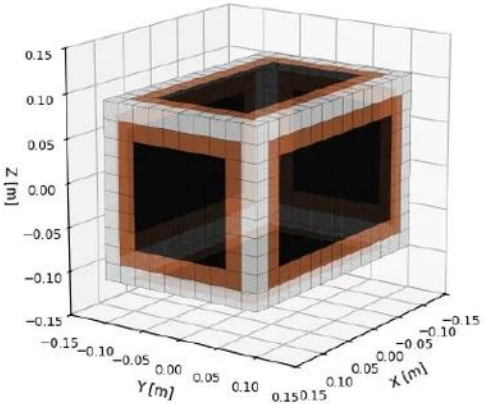
Solar radiation force and torque

$\mathbf{F}_{\text{SRP}}$ $\boldsymbol{\tau}_{\text{SRP}}$



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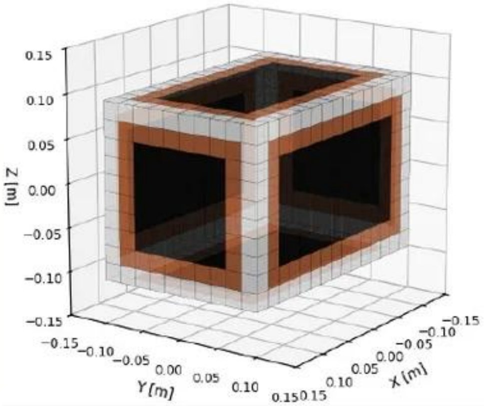

Solar radiation force and torque

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$\mathbf{F}_{\text{grav}}$ $\boldsymbol{\tau}_{\text{gg}}$

Thermal reradiation force and torque

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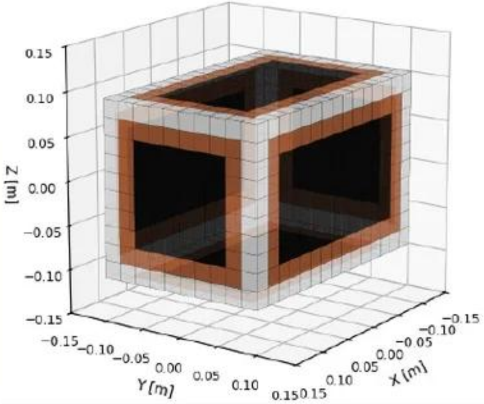

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$\mathbf{F}_{\text{SRP}}$ $\boldsymbol{\tau}_{\text{SRP}}$

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Thermal reradiation force and torque

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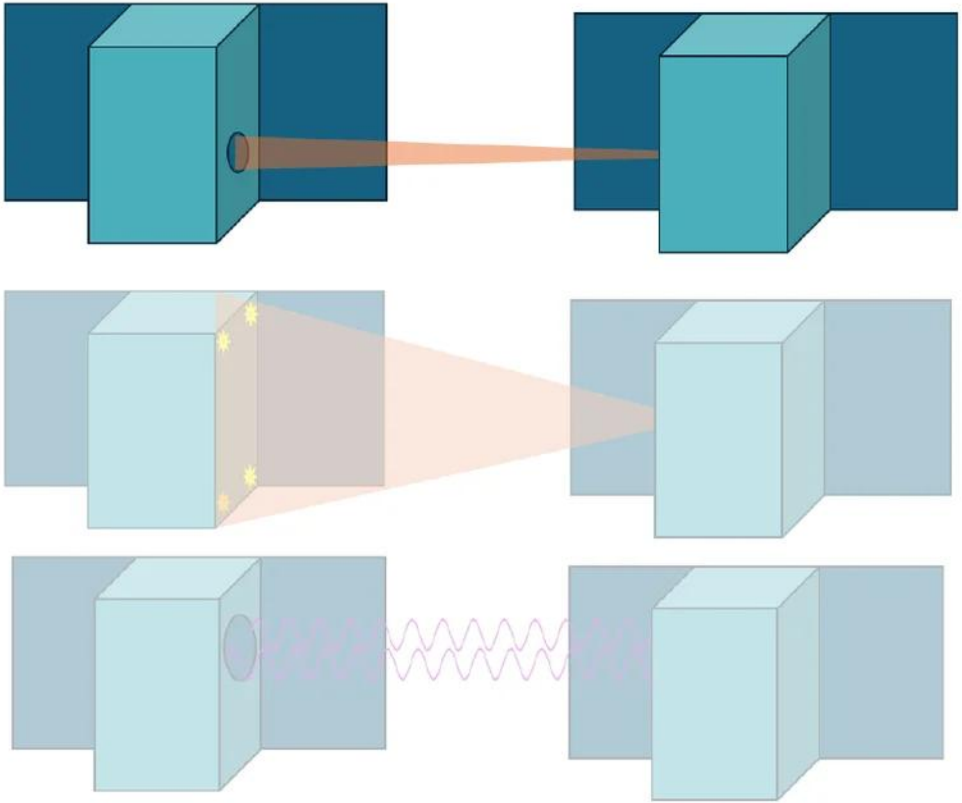
Earth albedo and infrared light force and torque

$\mathbf{F}_{\text{alb/IR}}$ $\boldsymbol{\tau}_{\text{alb/IR}}$

Inter-Satellite Sensors



Laser Metrology

LED Centroiding

Inter-Satellite Link

Laser Metrology

$$\rho_{\text{meas}} = \rho_{\text{true}} + \boxed{\delta\rho_{\text{shot}}} + \delta\rho_{\text{freq}} + \delta\rho_{\text{TTL}} + \delta\rho_{\text{thermal}}$$

$\delta\rho_{\text{shot}}$	Radiometric link budget with a **white noise draw** that scales inversely with the square root of that received power.

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ASTROLAB

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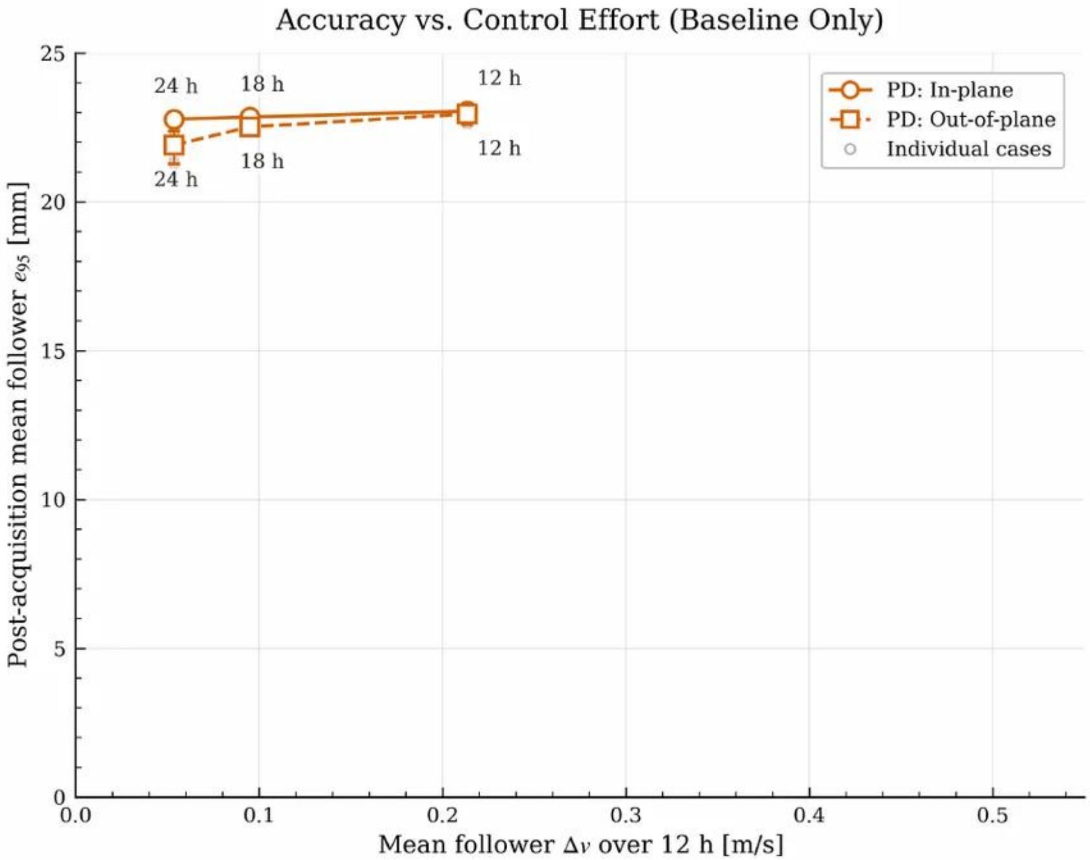
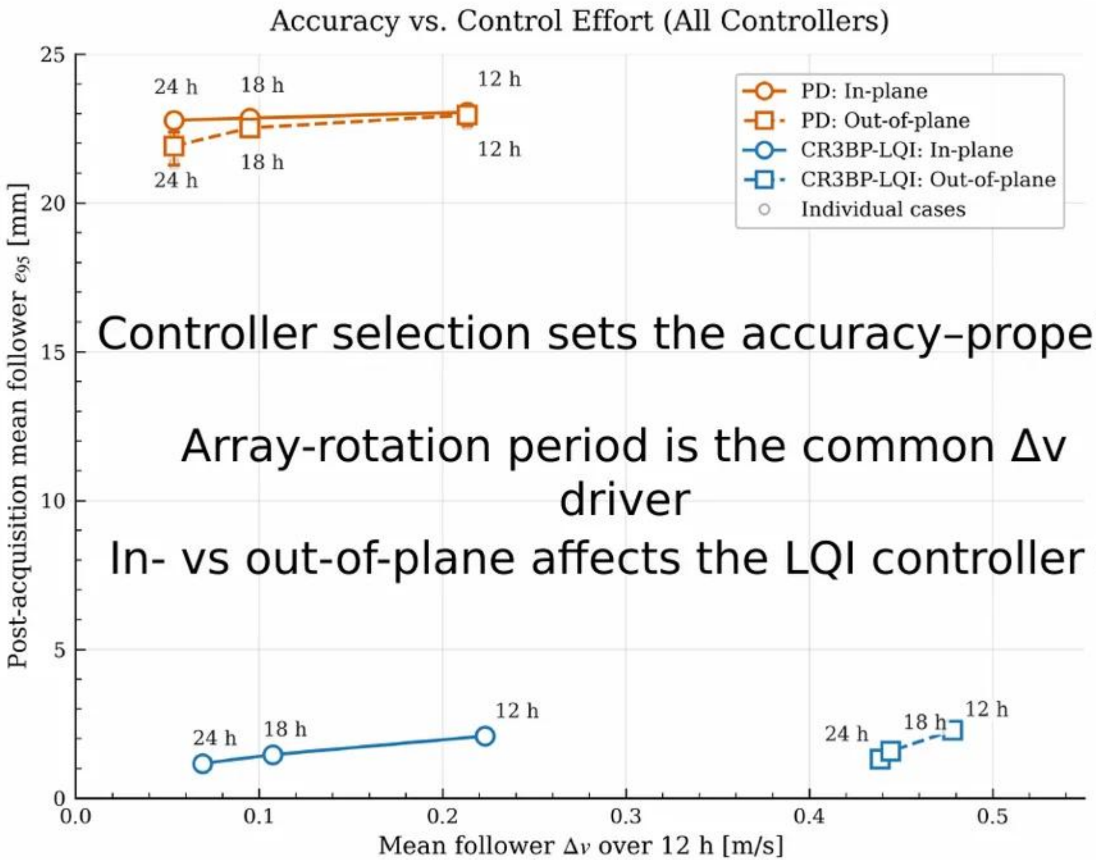
$\delta\rho_{\text{thermal}}$	Simulated via a **first-order Gauss-Markov random walk** applied directly to the body-frame metrology head mounting vectors.


Accuracy vs. Control Effort (Baseline Only)
Post-acquisition mean follower e_{95} [mm]
Mean follower Δv over 12 h [m/s]
24 h
18 h
12 h
24 h
18 h
12 h
PD: In-plane
PD: Out-of-plane
Individual cases
25
20
15
10
5
0
0.0
0.1
0.2
0.3
0.4
0.5



Controller selection sets the accuracy–propellant trade

Array-rotation period is the common Δv driver

In- vs out-of-plane affects the LQI controller only

Relative Factor Sensitivity Percentages

	Formation error		Control effort	
	CR3BP-LQI e_{95}	PD e_{95}	CR3BP-LQI Δv	PD Δv
Rotation period	57.3	2.9	33.0	132.6
Chief placement	9.2	1.9	109.2	0.0
Pointing angle	4.5	2.1	0.4	0.1
Chief orbit family	0.2	0.1	0.2	0.0

Key Takeaways

GNC and optical control must be co-designed: Formation errors couple directly into optical-path difference and planet-modulation error.

Controller selection sets the accuracy–propellant trade: CR3BP–LQI achieved 1–2 mm error, but came with the cost of higher Δv; with LQI, the out-of-plane combiner adds a large Δv penalty.

Array-rotation periods are the common Δv driver: Array rotation periods raise Δv, and substantially increase LQI formation error. Pointing angle and chief-orbit family were secondary.

Any Questions?

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